Actuation of a Thumb Prosthesis using Remaining Natural Fingers

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Abstract – A simple but useful concept for the actuation of finger prosthesis, using the ability of remaining natural fingers of a partially deformed human hand, is presented in this work. The design is based on very simple principles drawn from the concept of opposition space. A prosthetic mechanism for a hand, which has lost a thumb but retains the abilities of the other fingers, is developed as an example to demonstrate the concept. This presentation is a system integration of the concept, design, modeling, simulation and development of the prosthetic mechanism. The system is modeled using the powerful technique of Bond graphs. Effects such as extensibility of actuation strings and their internal damping, bearing friction at joints, etc., which are encountered in the prosthetic system, have been modeled and simulated. A simple prototype has been developed based on the proposed concept and demonstrates the effectiveness of the design. The prosthesis is very affordable and simple, and holds great promise for persons with such prehensile disabilities.

I. INTRODUCTION

The functional capabilities of the human hand are numerous and have been extensively studied and elaborated in literature [1], [2], [3], [4]. These include essential daily functions such as grasping, pinching, writing, twitching, squeezing, tying, etc. Injury to any part of the hand, and especially to the fingers, is therefore a severe loss to the affected person. It is therefore important to design prosthesis which can compensate for such severe losses.

Systematic classifications of the tasks performed by human hands have been provided by several researchers. One useful and appealing concept is that of opposition space constituted by virtual fingers. In the detailed work by Iberall [1], [2], it has been shown that all prehension tasks can be effectively reduced to this concept of opposition space. The pad opposition, palm opposition and side opposition are the basic primitives using which a human hand can operate and perform everyday tasks. This concept of opposition space can be used to design prosthesis to augment the capabilities of the impaired hand by providing motion capabilities to prosthetic fingers using one or more of the remaining natural fingers. This requires that the prosthetic finger should be able to move in a direction opposite to the remaining natural finger, which acts as an active link. This concept has been applied to the design of a prosthetic thumb which is actuated by one or more of the remaining active fingers.

In this work, we design and analyze a thumb prosthesis with capabilities to move and do a large class of manipulative tasks daily performed by the natural hand, such as gripping, writing, pinching, twiddling, etc... The thumb prosthesis is required to copy the movements of the index finger or other fingers, but in the opposite direction, as seen in a mirror. The effort to move the thumb is also to be derived from the movement of the other active finger on the same hand. The prosthesis can be worn on the hand as a partial glove. The mechanism proposed here can be used to design configurations which perform practically all the functional tasks mentioned in [2]. The mechanism is extremely simple and affordable.

The prosthetic device may be considered as a passive device, not drawing external power but from the hand alone. Such a passive prosthetic device is considered to be safe and human friendly. The prosthesis could also be designed to be a sophisticated active device, capable of handling more power, etc... Both the active and passive prostheses can also be fitted with sensors for measurement of variables, such as angles, forces, pressures, etc., in real time.

II. PROPOSED MECHANISMS

Two conceptual mechanisms are considered here, for the movement capabilities of the prosthetic thumb. The first one uses strings (as tendons) while the second one is based on fluid medium, e.g. water or air.

A. String (tendon) based mechanism

Consider the simple mechanism shown in Fig. 1. It consists of two links, the left one representing the thumb, a passive link in this case, and the right one representing a link attached to an active finger, say the index finger. Both these links are considered to be hinged on a third rigid link at L and R respectively. Two strings, almost inextensible, are used for actuation of the prosthetic
thumb joint. The first string (string 1) starts from point \( A \) and goes along the outer side of the active finger link, around the base pulley centered at \( R \) and on to the inner side of the passive thumb link, where it is attached at point \( P_1 \).

Fig. 1. A two-finger mechanism actuated by strings

The second string (string 2) starts from the point \( A \) and goes along the inner side of the active finger link, around another base pulley centered at \( R \) and on to the outer side of the passive thumb link, where it is attached at point \( P_2 \). The strings are required to be taut always. A string can actuate a finger link while it is in tension only. The strings can be passed through sheath tubing as in the case of bicycle brake wires. This can ensure constant string length between the pulleys, while maintaining appropriate string tension, even if the center distance \( LR \) changes. Further, the axes of rotation about \( L \) and \( R \) need not be parallel.

When the fingers are to be moved outwards, as shown by the direction sense \( m_1 \), the index finger, connected to the active finger link, moves outwards. A moment \( r_{m_1} \) is developed about the joint \( R \). This results in a force of tension \( F_{m_1} \), in string 2, which gets transmitted through the outer side of the passive thumb prosthesis. The thumb link experiences a moment in the opposite direction sense of \( r_{m_1} \), and opens (outward movement) about joint \( L \). In this case, string 1 remains passive and complies, while string 2 is active. When the fingers are to be moved inwards, as shown by the direction sense \( m_1 \), the index finger, connected to the active finger link, moves inwards. A moment \( r_{m_1} \) is developed about the joint \( R \). This results in a force of tension \( F_{m_1} \), in string 1, which gets transmitted through the inner side of the passive thumb prosthesis. The thumb link experiences a moment in the opposite direction sense of \( r_{m_1} \), and closes (inward movement) about joint \( L \). In this case, string 2 remains passive and complies, while string 1 is active.

B. Fluid based Mechanism

Consider the mechanism shown in Fig. 2. It has two links. Again, the left link represents the thumb, which is a passive prosthesis and the right link is attached to an active finger – say the index finger. One stem of each finger joint is fixed on a third link at \( L \) and \( R \) as shown in Fig. 2.

Fig. 2. Fluid based mechanism

Each joint shown consists of two chambers. The two stems on either side of the revolute joint are separated by diaphragm bellows. When the pressure in one chamber of the joint is greater than the pressure in its complementary chamber, the stems will tend to turn as shown in Fig. 3.

Fig. 3. Fluid based joint and its working.

It may be assumed that the initial quantity of fluid in the chambers of each joint is as required to maintain it in the desired position. The chamber \( A \) of joint at \( L \) is connected by thin tubing to the chamber \( A \) of joint at \( R \), and the chamber \( B \) of joint at \( L \) is connected to the chamber \( B \) of joint at \( R \), as shown in Fig. 2.

When the fingers are to be moved inwards, the index finger connected to the active right link moves inwards. This results in the squeezing of chamber \( B \) and expanding of chamber \( A \) of the joint at \( R \). Since the chambers between the joints are connected, the squeezing of chamber \( B \) at joint \( R \) results in expansion of chamber \( B \) at joint \( L \), and the expansion of chamber \( A \) of joint at \( R \) results in the squeezing of chamber \( A \) at joint \( L \). This results in movement of the thumb in the opposite direction, and the fingers move inwards towards each
other. In the same way, the fingers can also be moved outwards.

III. MODELING AND SIMULATION OF THE STRING BASED MECHANISM

A model of the dynamics of the prosthetic system can help in analyzing, simulating and understanding the detailed working of the mechanism. We now proceed to construct such a model, for the string based mechanism, using the method of Bond graphs invented by Henry Paynter. The model is pictorial and based on the interaction of power between the elements of the system. Cause-effect relationships are also depicted and help in deriving the system equations in an algorithmic manner. Details about the method, and the art of constructing Bond graphs can be found in [5] and [6].

When the active index finger is moved inwards, as in closing the grip, \( \theta_R \) increases – counter clockwise, and a moment \( \tau_{R_1} \) is applied about joint R. Junction \( J_1 \) represents the common flow variable \( \dot{\theta}_R \). \( J_1 \) is the element showing the effort variable, torque \( \tau_R \), applied at junction \( J_1 \), as a result of movement of the active finger. \( J_1 \) is the moment of inertia of the active link about the axis at R, normal to the plane. The string tension of magnitude \( F_s \), is represented by the \( 0_{R_1} \) junction. The transformer element \( TF : r_{R_1} \) relates this force to the moment it generates about the joint R. Due to its power conserving nature, it also relates the angular velocity component \( \dot{\theta}_R \) to the speed of winding of the string \( \dot{s}_1 \). Junction \( J_2 \) represents the common flow variable \( \dot{\theta}_R \). The rotary inertia of the passive finger link, about the joint L, is modeled by \( I : J_2 \). Two paths have been shown in the Bond graph between the \( J_1 \) and \( J_2 \) junctions. These are on account of the two strings 1 and 2.

The radius of the base pulley at \( R \) for string 2 can be different, and has been shown intentionally to be so, using the transformer element \( TF : r_{R_1} \). It also relates the angular velocity \( \dot{\theta}_R \) to the speed of winding of the string \( \dot{s}_2 \).

The relationship between the velocities \( \dot{\theta}_L \) and \( \dot{\theta}_R \) given by both the paths should however be the same, i.e.,

\[
\dot{\theta}_L = \frac{r_{L_1}}{r_{L_2}} \dot{\theta}_R = -\frac{r_{L_1}}{r_{L_2}} \dot{\theta}_R \quad \text{and in order to ensure}
\]

\[
\text{this, } \frac{r_{L_1}}{r_{L_2}} = \frac{r_{L_1}}{r_{L_2}}
\]

Amplification of torque, or movement, can be achieved by designing the above ratios to be suitable to the requirement.

The stiffness and internal damping effects of the string can be modeled using elements \( C : K_s \) and \( R : R_s \) as shown. \( K_s \) depends on the Young’s modulus of the string along its length. It is assumed that (1) the forces are within the limits of impending slippage. (2) The surface speed of the string is the same as that of the pulley at contact.

The surface speeds of the left (\( L \)) and right (\( R \)) pulleys, through which string \( L \) passes, are shown by junctions \( 0_{p_J} \) and \( 0_{e_J} \) respectively. \( e_{11} \) and \( e_{13} \) are the effort variables, decided by properties of string \( L \) and \( R \), and applied on junctions \( 0_{p_J} \) and \( 0_{e_J} \) respectively. Since the strings are able to transmit tensions only, the following conditions apply:

\[
F_s = 0, \text{ i.e., } e_{11} = 0, \text{ if } e_{11} < 0, \text{ and }
\]

\[
F_s = 0, \text{ i.e., } e_{13} = 0, \text{ if } e_{13} < 0
\]

The system has four state variables: \( p_i \) and \( p_2 \) are the angular momenta of the active finger and the passive finger respectively. \( q_i \) and \( q_3 \) are the extensions of strings \( L \) and \( R \) respectively. Equations (3), (4), (5) and (6) are the four state equations representing the dynamics of the system, derived algorithmically from the Bond graph [6].

\[
\dot{p}_j = r_{R_i} + r_{R_2} \left( K_s q_s + R_s \left[ \frac{r_{L_i}}{J_s} p_i - \frac{r_{L_s}}{J_p} p_2 \right] \right)
\]

\[
-\frac{r_{L_1}}{J_s} q_s + R_s \left[ \frac{r_{L_i}}{J_s} p_i + \frac{r_{L_s}}{J_p} p_2 \right]
\]

2000
\[
\dot{q}_1 = -r_n \left( K_x q_1 + R_x \left[ \frac{r_n}{J_P} p_1 + \frac{r_n}{J_P} p_2 \right] \right) \\
+ r_n \left( K_x q_1 + R_x \left[ -\frac{r_n}{J_P} p_1 - \frac{r_n}{J_P} p_2 \right] \right) \\
\dot{q}_2 = \frac{r_n}{J_A} p_1 + \frac{r_n}{J_A} p_2 \\
\dot{p}_1 = -\frac{r_n}{J_A} p_1 - \frac{r_n}{J_A} p_2 \\
\dot{p}_2 = -\frac{r_n}{J_A} p_1 + \frac{r_n}{J_A} p_2 
\]

(4) (5) (6)

The model has been simulated with an initial posture such that \( \theta_\alpha = 60^\circ \) and \( \theta_\beta = 120^\circ \). The active finger is supplied a torque \( \tau_\phi = 0.0005\sin(\pi t) \) N-m so that the fingers may close and open. The parameters chosen are: \( J_A = 1 \times 10^{-3} \text{Kg.m}^2 \), \( J_P = 1.2 \times 10^{-3} \text{Kg.m}^2 \), \( K_n = 1 \times 10^{1} \text{N.m} / \text{m} \), \( K_n = 1 \times 10^{1} \text{N.m} / \text{m} \), \( R_n = 0.1 \text{N.s/m} \), \( R_n = 0.1 \text{N.s/m} \), \( r_n = 0.01 \text{m} \), \( r_n = 0.01 \text{m} \), \( r_n = 0.01 \text{m} \), \( r_n = 0.01 \text{m} \), \( R_{R_n} = 0.0001 \text{N.m.s} \), \( R_{R_n} = 0.0001 \text{N.m.s} \). The simulation is for a duration of 2 s. Results of the simulation are shown and discussed here.

Fig. 5. Angular displacement of joints. The fingers are made to close and open. The passive finger follows the movement of the active finger in the reverse direction, as desired.

Fig. 6. String extensions. Oscillations, although small, are due to the axial stiffness of the strings.

Fig. 7. Tension in strings. It may be observed that string 2 is relaxed when string 1 is in tension, and vice-versa.

Fig. 8. Account of Power transactions. The distribution of input power for movement of the fingers and the power losses in bearings are depicted here.

2001
IV. DEVELOPMENT OF THE PROTOTYPE AND ISSUES INVOLVED

An experimental prototype of the string based prosthetic mechanism has been developed to demonstrate the concept and analyze its effectiveness. Photographs of the string based prototype are shown in Fig. 9 and Fig. 10. The prosthetic device is made of Aluminium components. The steel string used is multi-strand wire of 1mm diameter. Bearings have been used at the two joints $L$ and $R$ to reduce friction.

![Fig. 9. Closing movement. The active link, on the right, is moved inwards and the passive link follows inwards too. It may be noted that the dimensions used for the prototype are almost the same as those of actual human fingers.](image)

![Fig. 10. Photograph of the string based mechanism showing opening movement. The active link, on the right, has been held with the right hand and is moved outwards. The passive link, on the left, moves outwards too.](image)

A. Some Issues for consideration in the proposed mechanisms.

Issues arising in the design and development of the proposed mechanisms are briefly addressed here.

The string based prosthetic mechanism can be designed to provide either increased torque or increased movement on the passive thumb joint. The ratio of diameters of the pulleys mounted at $L$ and $R$ can be designed for the desired effect.

The strings should be strong enough to bear the forces produced in performing everyday human tasks. The string should have a high Young’s modulus so as to have very little extensibility. Multi-strand wire is found to be suitable. The string tightness should be adjusted to have desirable stiffness. Sheath tubing can be provided around the string fibers to maintain the string taut, as in the brake wire arrangement for bicycles. This allows the mechanism to be adequately flexible as required for human beings. The frictional force between the string and the sheath tubing should be as low as possible.

The rigid links should be as light as possible and strong at the same time. Aluminium is suitable for links and joints of the prosthesis. The mechanism should be wearable as a glove on the partially disabled hand.

![Fig. 11. Modularity of joints. Modularity allows extension of more DOFs to the mechanism.](image)

There is ample scope to explore additional desirable abilities, such as, changing impedance of the finger, and mechanism for locking in any posture. A very important issue is that of adding more degrees to the mechanism for more dexterous manipulation. Modularity of the joints and links permit extension of the mechanism as shown in Fig. 11.

Liquid medium, such as water, can also be used instead of air, to avoid effects of compressibility in the fluid based mechanism. Tubes carrying the liquid are required to be strong enough to withstand pressure during operation. Connection of tubing to the chambers at joints should be carefully implemented to prevent leakage. In order to have initial desirable joint stiffness and hand posture, fluid quantity in each chamber needs adjustment.
V. SUMMARY AND CONCLUSION

This work shows a way of utilizing the ability of remaining natural fingers of a partially deformed human hand to provide movement to a prosthesis. The concept is simple and based on the idea of opposition space. The concept has been demonstrated using an example of a prosthetic mechanism for a hand, which has lost a thumb but retains the abilities of the other fingers. An integrated systems approach is used to present the concept, design, modeling, simulation and development of the prosthetic mechanism. A Bond graph model for the system has been presented, considering effects of extensibility of actuation strings and their internal damping, bearing friction at joints, etc., which are encountered in the prosthetic system. A simple prototype, extremely cost effective, based on the proposed concept, has been developed. The effectiveness of the design has been demonstrated. The concept offers modularity and extension of more degrees of freedom for better dexterity. It is hoped that various aspects discussed in this work will be explored further to fulfill the hopes of many disabled persons.

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VII. REFERENCES